7. LANDFILLING

This chapter presents estimates of GHG emissions and carbon sequestration from landfilling of (1) each of the ten materials considered in this analysis, and (2) mixed MSW.

When food scraps, yard trimmings, and paper are landfilled, anaerobic bacteria degrade the materials, producing methane (a potent GHG) and carbon dioxide. The carbon dioxide is not counted as a GHG because it is biogenic, as explained in Section 1.6. Because metals do not contain carbon, they do not generate methane when landfilled. Plastics are essentially not biodegradable, and therefore do not generate any methane.

Because food scraps, yard trimmings, and paper are not completely decomposed by anaerobic bacteria, some of the carbon in these materials is sequestered in the landfill. However, carbon in plastic that remains in the landfill is not counted as sequestered carbon (as described in Section 1.4).

Transportation of waste materials to a landfill results in anthropogenic carbon dioxide emissions, due to the combustion of fossil fuels in the vehicles used to haul the wastes.

For this study, we estimated the methane emissions, anthropogenic carbon dioxide emissions, and carbon sequestration that will result from landfilling each type of organic waste, and from landfilling mixed MSW. We accounted for the extent to which methane will be flared at some landfills, and will be combusted for energy recovery at others. In both cases, we projected future landfill gas (LFG) recovery rates based on a significant increase in the use of LFG recovery systems due to a new EPA rule that requires gas recovery at large MSW landfills.[84]

Our results showed that landfilling of office paper results in substantial positive net GHG emissions, and that landfilling of food scraps and grass have small positive net GHG emissions (in absolute terms). For these three materials, the net GHG emissions from methane generation exceed the carbon sequestration (for the fraction of these materials that does not degrade in landfills). For all of the other materials that we examined, landfilling results in negative net GHG emissions in absolute terms · ranging from slight negative net emissions for corrugated boxes, mixed MSW, and yard trimmings,[85] to moderate negative net emissions for branches, leaves, and newspaper. For these materials, carbon sequestration exceeds the net GHG emissions from methane generation (after accounting for projected LFG recovery).

The results would differ if a different assumption were used for the percentage of landfill methane recovered in the year 2000. At lower (e.g., current) rates of LFG recovery, the net GHG emissions of office

---

[84] The rule requires a well-designed and well-operated landfill gas collection system at landfills that (1) have a design capacity of at least 2.5 million metric tons, or 2.5 million cubic meters, and (2) emit more than 50 metric tons of nonmethane organic compounds per year (Federal Register, Vol. 61, No. 49, p. 9905, March 12, 1996).

[85] Yard trimmings were estimated to consist of 50 percent grass clippings, 25 percent leaves, and 25 percent branches from trees and shrubs.

paper, food scraps, and grass increase further, and the net GHG emissions of corrugated boxes, yard trimmings, and mixed MSW turn from negative to positive.

7.1   EXPERIMENTAL VALUES FOR METHANE GENERATION AND CARBON SEQUESTRATION

To estimate methane emissions and carbon sequestration from landfilling of specific materials, we used data from laboratory experiments conducted by Dr. Morton Barlaz.[86] The experiments provided data on (1) the amount of methane generated by each type of organic material, when digested by bacteria in anaerobic conditions simulating those in a landfill, and (2) the amount of carbon remaining, undecomposed (i.e., sequestered) at the end of the experiment.

Experimental Design

Barlaz placed each type of organic waste and mixed MSW in separate reactor vessels, in which he maintained anaerobic conditions similar to those in a landfill, but controlled to favor maximum methane generation. Barlaz measured the amount of methane generated in each reactor, and the amount of undecomposed carbon remaining in each reactor at the end of the experiment. Each material was tested in four reactors, and the results from each were averaged.[87]

At the start of the experiment, Barlaz dried a sample of each material, and analyzed the amount of cellulose, hemicellulose, and lignin (and, for food scraps, protein) in each material. Cellulose, hemicellulose, and protein partly decompose in a landfill, resulting in methane generation; lignin is relatively stable and non-decomposable under anaerobic conditions.

Portions of each material were weighed, placed in two-liter plastic containers (i.e., reactors), and allowed to decompose anaerobically under warm, moist conditions designed to accelerate decomposition. The reactors were seeded with a small amount of well-decomposed refuse containing an active population of methane-producing microorganisms (the "seed"), to ensure that methane generation was not limited due to an insufficient population of microorganisms. To promote degradation, water was cycled through each reactor. Nitrogen and phosphorus were then added so that methane generation would not be limited by a lack of these nutrients.

The reactors were allowed to run for periods varying from three months to two years. The experiment ended for each reactor when one of two conditions were met: (1) no measurable methane was being emitted (i.e., any methane that was being emitted was below the detection limits of the analytical equipment), or (2) a curve generated mathematically from an analysis of the reactor's prior methane generation indicated that the reactor had produced at least 95 percent of the methane that it would produce if allowed to run forever.

---

[86] Barlaz's work was funded by EPA's Air and Energy Engineering Research Laboratory under the supervision of Susan Thorneloe.

[87] Barlaz, Morton, "Measurement of the Methane Potential of the Paper, Yard Waste, and Food Waste Components of Municipal Solid Waste," unpublished paper, Department of Civil Engineering, North Carolina State University, Raleigh, NC, 1994.

Barlaz measured the amount of methane generated during the experimental period, and subtracted the amount of methane attributable to the seed in order to obtain the amount of methane generated by the material being tested. At the end of the experiment, he opened the reactors, drained the leachate, dried and weighed the contents, and analyzed the percentage composition of cellulose, hemicellulose, and lignin (and, for food scraps, protein) in the remaining contents. He then measured the percentage of total volatile solids in the remaining contents. This amount included the cellulose, hemicellulose, lignin, and protein, and any other carbon-containing components such as waxes and tannins.

We used the experimental results that Barlaz obtained to first estimate the amount of each carbon-containing component remaining that was attributable to the seed,[88] and then to estimate the amount of carbon for each material that remained. We assumed that the experiment reflected landfill conditions, and that organic carbon remaining undegraded in the reactors would also remain undegraded over the long term in landfills, i.e., it would be sequestered.

Methane Generation: Experimental Data and Adjusted Values

The amount of methane generated by each type of organic material (after deducting the methane attributable to the seed), is shown in column "b" of Exhibit 7-1.[89]

As a check on his experimental results, Barlaz estimated the amount of methane that would have been produced if all of the cellulose, hemicellulose, and protein from the waste material that was decomposed during the experiment had been converted to equal parts of methane and carbon dioxide (methane-producing microorganisms generate equal amounts, by volume, of methane and carbon dioxide gas).[90] Barlaz referred to this amount as the material's "methane potential." He then calculated the percentage of the methane potential for each material accounted for by the sum of (1) the measured methane generation, and (2) the amount of methane that could be formed from the carbon in the leachate that was removed from the reactor, and from the carbon in the refuse that remained in the reactor at the end of the experiment.[91] The resulting percentages of the methane potential accounted for are shown in column "c" of Exhibit 7-1. Methane potential <u>not</u> accounted for could be due to either (1) leaks of methane, (2) measurement error, or (3) carbon in the cell mass of microorganisms (which was not measured).

Methane recovery was below 85 percent of the "methane potential" for four materials: office paper, food scraps, leaves, and branches. In using Barlaz's data, we needed to make a choice regarding how to allocate this missing carbon. We chose to assume that some of it had been converted to microorganism cell mass, and the remainder had been degraded. Barlaz postulated a higher methane yield based on assumptions that (1) five percent of the carbon in cellulose and hemicellulose (and protein in the case of food scraps) that was degraded was converted into the cell mass of the microbial population, and (2) 90 percent of the carbon-

---

[88] Dr. Barlaz tested seed alone to be able to control for the amount of methane generation and carbon sequestration that was attributable to the seed.

[89] Personal communication from Dr. Morton Barlaz to Clare Lindsay, U.S. EPA, July 20, 1995.

[90] Ibid. Lignin was not considered in this check because cellulose, hemicellulose, and protein account for nearly all of the methane generated.

[91] Note that any carbon that was converted to cell mass in microorganisms was not considered in this calculation.

containing compounds that were degraded but not converted to cell mass were converted to equal parts of methane and carbon dioxide. The "corrected yields," based on these assumptions, are shown in column "d" of Exhibit 7-1.

We decided, in consultation with Barlaz, to use the "corrected yields" for leaves, branches, and office paper because we believed that these values were more realistic than the measured yields.[92]

The methane values that we used for each material (either the measured yield, or the "corrected" yield) are shown again in column "f" of Exhibit 7-1. In order to maintain consistent units with the other parts of our analysis, we converted the units for methane generation from milliliters per dry gram of waste, to metric tons of carbon equivalent (MTCE) per wet ton of waste.[93] The resulting values are shown in column "g" of Exhibit 7-1. The value for yard trimmings is a weighted average of the values for grass, leaves, and branches, based on an assumption that yard trimmings are composed of 50 percent grass, 25 percent leaves, and 25 percent branches (on a wet weight basis).[94]

Carbon Sequestration: Experimental Data and Calculations

To estimate the amount of carbon sequestered when each material is landfilled, we used data from Barlaz's experiments on the amount of carbon-containing components in (1) the material placed in the reactors at the start of the experiment, (2) the "seed" added to each reactor, and (3) the material remaining in each reactor at the end of the experiment. We also used data on the total dry weight of both the sample of waste material and the seed placed in each reactor.

In essence, we used these data to estimate carbon sequestration by calculating the amount of carbon remaining in each reactor at the end of the experiment, and then subtracting the amount of carbon remaining that was attributable to the seed. The difference between the two values is the amount of carbon from the waste material that remained in the reactor, undecomposed, at the end of the experiment. Because the conditions in the reactor simulated landfill conditions, approximately this amount of carbon would be sequestered if the material were landfilled. For each material, we averaged the carbon sequestration values for the four reactors. Our results are shown in Exhibit 7-2; our approach to estimating carbon sequestration is described in more detail in the explanatory notes accompanying that exhibit.

---

[92] For food scraps, however, even though the methane potential recovery percentage was lower than 85 percent, we used the measured yield, as shown in column "b." We made this choice for food scraps because the "corrected yield" for food scraps was greater than the maximum possible yield (shown in column "e" of the exhibit). Barlaz had calculated the maximum possible yield for each material based on the methane yield if all of the cellulose, hemicellulose, and protein in the material: (1) decomposed and (2) were converted to equal parts of methane and carbon dioxide.

[93] To make the conversion, we used the ratio of dry weight to wet weight for each material and a global warming potential of 24.5 for methane.

[94] As noted in chapter 5, this professional judgment estimate for the percentage composition of yard trimmings (as a national average) was provided by Nick Artz of Franklin Associates, Ltd. in a telephone conversation with William Driscoll of ICF Incorporated, November 14, 1995.

Exhibit 7-1
Methane Yield and Methane Generation for Solid Waste Components

(a) Material	(b) Average Measured Methane Yield (ml per dry gm)	(c) Percentage of "Methane Potential" Accounted For	(d) "Corrected" Methane Yield (ml per dry gram)	(e) Maximum Possible Methane Yield (ml per dry gram)	(f) Selected Methane Yield (ml per dry gm)	(g) Selected Methane Yield (MTCE / wet ton)
Newspaper	74.2	98.0	NA	239.4	74.2	0.302
Office Paper	217.3	55.5	346.0	398.2	346.0	1.408
Corrugated Boxes	152.3	87.7	NA	279.7	152.3	0.626
Food Scraps	300.7	77.4	386.2	357.6	300.7	0.391
Grass	144.3	89.3	NA	153.2	144.3	0.250
Leaves	30.5	75.2	56.0	108.0	56.0	0.194
Branches	62.6	82.8	76.3	224.9	76.3	0.198
Yard Trimmings						0.223
Mixed MSW	92.0	97.6	NA	157.6	92.0	0.319

Explanatory note: Because Dr. Barlaz based his measurements on the dry weight of each material, the units throughout most of this exhibit are also provided in terms of methane generation per unit of dry weight. But because MSW is measured in its wet form (i.e., in tons of MSW "as is;" not dried), the units are converted to methane generation per wet ton in the last column of the exhibit. Note that no values are shown for yard trimmings until the last column of the exhibit, because the yard trimmings value is based on the estimated proportions of grass, leaves, and branches contained in yard trimmings, weighed on a <u>wet</u> basis.

Exhibit 7-2
Carbon Sequestration for Solid Waste Components

(a) Material	(b) Ratio of Carbon Sequestration to Dry Weight (gm C/dry gm)	(c) Ratio of Dry Weight to Wet Weight	(d) Ratio of Carbon Sequestration to Wet Weight (gm C/wet gm)	(e) Amount of Carbon Sequestered (MTCE per Wet Ton)
Newspaper	0.40	0.94	0.38	0.34
Office Paper	0.04	0.94	0.04	0.04
Corrugated boxes	0.26	0.95	0.25	0.23
Food Scraps	0.31	0.30	0.09	0.08
Grass	0.22	0.40	0.09	0.08
Leaves	0.42	0.80	0.34	0.30
Branches	0.38	0.60	0.23	0.21
Yard Trimmings			0.19	0.17
Mixed MSW	0.20	0.80	0.16	0.14

Explanatory notes:

(1) To determine the amount of carbon remaining in each reactor at the end of the experiment, we used (1) the measured amount of each carbon-containing component -- cellulose, hemicellulose, lignin, protein (for food scraps), and total volatile solids -- remaining in each reactor,[95] and (2) estimates of the amount of carbon in each carbon-containing component. To estimate the second data element, we used the following data sources:

- Cellulose: we used the chemical formula to determine that cellulose is 44.4 percent carbon (on a mass basis).

- Hemicellulose: There are various types of hemicellulose; we used a composite chemical formula to estimate that the carbon content is 45.5 percent.[96]

- Lignin: The *Encyclopedia of Chemical Technology* reports the "average elementary analysis for wood lignin" for coniferous species to be 63.8 percent carbon.[98]

- Protein: There are many types of protein; we used a carbon content of 53.8 percent from a composite composition for protein.[99]

---

[95] Personal communication from Dr. Morton Barlaz to Randy Freed, ICF Incorporated, July 19, 1995.

[96] U.S. Environmental Protection Agency, *Estimate of Methane Emissions from U.S. Landfills* (Washington, D.C.: U.S. EPA) September 1994, p. 6.

[98] Kirk-Othmer, *Encyclopedia of Chemical Technology, Third Edition* (New York: John Wiley & Sons) 1981, Vol. 14, p. 298.

[99] Barlaz, Morton A. and Robert K. Ham, "The Use of Mass Balances for Calculation of the Methane Potential of Fresh and Anaerobically Decomposed Refuse," in *Proceedings from the GRCDA 13th Annual International Landfill Gas Symposium March 27-29, 1990* (Silver Spring, MD: GRCDA · The Association of Solid Waste Management Professionals) 1990, p. 232.

Explanatory notes for Exhibit 7-2 (continued):

- Other carbon-containing components (i.e., total volatile solids minus cellulose, hemicellulose, lignin, and protein): These components consist largely of waxes and tannins, so we used the average carbon content from two relevant compounds · the wax in Douglas fir bark (58.7 percent carbon) and tannic acid (53.65 percent carbon).[100] The average of these values was 56 percent carbon.

(2) We next estimated the amount of carbon remaining in each reactor that was attributable to the seed. Barlaz used the same type of seed for all materials except food scraps. For the predominant type of seed, we first determined the average amount of carbon remaining in the four seed reactors (i.e., those reactors containing only seed) at the end of the experiment: 14.6 percent of the total dry weight of the seed entering the reactor. For all materials but food scraps, we used this percentage, together with the dry weight of the seed entering each reactor, to estimate the amount of carbon sequestration in each reactor that was attributable to seed.[101]

(3) We used the estimates for the amount of carbon remaining in each reactor, and the amount attributable to seed, to develop an average ratio, for each material, of (1) the amount of carbon sequestered (after deducting the amount attributable to seed) to (2) the dry weight of waste material placed in the reactor. These ratios are shown in column "b" of the exhibit.

(4) Because MSW is typically measured in terms of its wet weight, we needed to convert the ratios for carbon sequestered as a fraction of dry weight to carbon sequestered as a fraction of wet weight. To do this, we used the estimated ratio of dry weight to wet weight for each material. These ratios are shown in column "c" of the exhibit. For most of the materials, we used data from an engineering handbook.[102] For grass, leaves, and branches, we used data provided by Barlaz.[103] To determine the ratio of carbon sequestration to wet weight of each material, we multiplied the values in columns "b" and "c." The results are shown in column "d."

(5) For consistency with the overall analysis, we converted the carbon sequestration values for each material to units of metric tons of carbon equivalent (MTCE) sequestered per short ton of waste material landfilled. The resulting values are shown in column "e" of the exhibit.

(6) We also used Barlaz's data for mixed MSW to estimate the percentage of carbon in mixed MSW that is sequestered in a landfill. Specifically, we used data on (1) the amount of carbon in each sample of mixed MSW initially placed in a reactor (based on the amounts of cellulose, hemicellulose, lignin, and other volatile solids in each sample, and the percentage carbon content of these components), and (2) the amount of carbon remaining in each mixed MSW reactor at the end of the experiment. The average percentage of carbon sequestered in the four samples of mixed MSW was 50 percent.

---

[100] The molecular formula for Douglas fir bark wax is from Kirk-Othmer, *Encyclopedia of Chemical Technology, Third Edition*, (New York: John Wiley & Sons) 1984, vol. 24, p. 470. The molecular formula for tannic acid is from Merck & Co., *The Merck Index, Eleventh Edition* (Rahway, NJ: Merck & Co., Inc.) 1989, p. 9027.

[101] For the seed used for food scraps, Dr. Barlaz collected data on the amount of cellulose, hemicellulose, and lignin remaining in the seed reactors at the end of the experiment, but did not collect this data on the protein remaining in the seed reactors. Thus, for food scraps, we assumed that the amounts of protein remaining in each reactor that had originated from the waste and from the seed, respectively, were in the same proportion as the amounts of protein in waste and protein in seed placed in the reactor initially.

[102] Tchobanoglous, George, Hilary Theisen, and Rolf Eliassen, *Solid Wastes: Engineering Principles and Management Issues* (New York: McGraw-Hill Book Co.) 1977, pp. 58 and 60.

[103] Dr. Morton Barlaz, personal communication with Joanne Colt, ICF Incorporated, April 25, 1995.

7.2   FATES OF LANDFILL METHANE: CONVERSION TO CO_2 EMISSIONS, AND FLARING OR COMBUSTION WITH ENERGY RECOVERY

In this analysis, we accounted for (1) the conversion in the landfill of some portion of landfill methane to CO_2, and (2) the capture of methane, either for flaring or for combustion with energy recovery (in either case, the captured methane is converted to CO_2).[104] Exhibit 7-3 presents this analysis.

The exhibit begins with the methane generation per wet ton of each material, which is shown in column "b" (the values were simply copied from the last column of Exhibit 7-1). The next three sections of the spreadsheet calculate net GHG emissions from methane generation for each of three categories of landfills: (1) landfills without LFG recovery, (2) landfills with LFG recovery that flare LFG, and (3) landfills with LFG recovery that generate electricity from the LFG. The second to last section of the spreadsheet shows the expected percentage of landfills in each category in 2000. The final column shows the weighted average GHG emissions from methane generation across all types of landfills in 2000.

To estimate MSW methane emissions from each category of landfill, we first needed to estimate the percentage of landfill methane that is oxidized near the surface of the landfill. We estimated that 10 percent of the landfill methane that is generated is either chemically oxidized or converted by bacteria to CO_2, and that the remaining 90 percent is available for atmospheric methane emissions.[105]

To estimate MSW methane emissions from landfills with LFG recovery, we used an estimate that these landfills will have an average LFG recovery efficiency of 85 percent by 2000.[106] In Exhibit 7-3 we show the percentage of methane that will <u>not</u> be captured by these landfills (i.e., 15 percent) in two columns (once for each of the two categories of landfills with LFG recovery).

To estimate net GHG emissions from methane generation for landfills that combust LFG to generate electricity, we estimated the utility GHG emissions avoided per unit of methane combusted for energy recovery (our calculations to develop this estimate are shown in Exhibit 7-4.

We also projected the percentage of MSW disposed in each category of landfill in 2000. We estimated that by the year 2000, when large landfills with substantial LFG emissions will have been required to recover LFG, 58 percent of all landfill methane will be generated at landfills with recovery systems, and 42 percent will be generated at landfills without LFG recovery.[107] Of the 58 percent of all methane generated at landfills with LFG recovery, 91 percent (or 53 percent of all methane) is expected to be generated at landfills that use LFG to generate electricity, and 9 percent (or 5 percent of all methane) at

---

[104] The CO_2 that is emitted is not counted as a GHG because it is biogenic in origin (as described in Section 1.6).

[105] U.S. EPA, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, D.C.: U.S. EPA) April 1993, page 4-20.

[106] Memorandum from Cindy Jacobs of the U.S. EPA Atmospheric Pollution Prevention Division to Michael Podolsky of the U.S. EPA Office of Policy, Planning and Evaluation, July 25, 1995.

[107] Based on data on (1) year 2000 MSW landfill methane generation of 64.5 million MTCE, (2) year 2000 landfill methane recovery of 40.0 million MTCE, and (3) projected year 2000 landfill methane recovery efficiency of 85 percent (all from the memorandum from Cindy Jacobs, op cit.).

Exhibit 7-3
Net GHG Emissions from Methane Generation

(a)	(b)	Methane from Landfills Without Methane Recovery		Methane from Landfills With LFG Recovery and Flaring			Methane from Landfills With LFG Recovery and Electricity Generation					Percentage of Methane From Each Type of Landfill in 2000			TOTAL
		(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
Material	CH4 Generation (MTCE/ Wet Ton)	Percentage Of Methane Not Oxidized to CO2	Net GHG Emissions from CH4 Generation (MTCE/ Wet Ton)	Percentage of Methane Not Recovered (100 % Minus Recovery Efficiency)	Percentage of Methane Not Recovered That is Not Oxidized to CO2	Net GHG Emissions From CH4 Generation (MTCE/ Wet Ton)	Percentage of Methane Not Recovered That is Not Oxidized to CO2	Methane Emissions (MTCE/ Wet Ton)	Utility CO2 Emissions Avoided Per MTCE CH4 Combusted (MTCE)	Utility CO2 Emissions Avoided (MTCE/ Wet Ton)	Net GHG Emissions From CH4 Generation (MTCE/ Wet Ton)	Percentage of Methane From Landfills Without LFG Recovery in 2000	Percentage of Methane From Landfills With LFG Recovery and Flaring in 2000	Percentage of Methane From Landfills With LFG Recovery and Electricity Generation in 2000	Net GHG Emissions From CH4 Generation (MTCE/ Wet Ton)
New spaper	0.302	90%	0.27	15%	90%	0.04	90%	0.04	0.09	0.02	0.02	42%	5%	53%	0.13
Office Paper	1.408	90%	1.27	15%	90%	0.19	90%	0.19	0.09	0.11	0.08	42%	5%	53%	0.58
Corr. Boxes	0.626	90%	0.56	15%	90%	0.08	90%	0.08	0.09	0.05	0.04	42%	5%	53%	0.26
Food Scraps	0.391	90%	0.35	15%	90%	0.05	90%	0.05	0.09	0.03	0.02	42%	5%	53%	0.16
Grass	0.250	90%	0.22	15%	90%	0.03	90%	0.03	0.09	0.02	0.01	42%	5%	53%	0.10
Leaves	0.194	90%	0.17	15%	90%	0.03	90%	0.03	0.09	0.02	0.01	42%	5%	53%	0.08
Branches	0.198	90%	0.18	15%	90%	0.03	90%	0.03	0.09	0.02	0.01	42%	5%	53%	0.08
Yard Trimmings	0.223	90%	0.20	15%	90%	0.03	90%	0.03	0.09	0.02	0.01	42%	5%	53%	0.09
Mixed MSW	0.319	90%	0.29	15%	90%	0.04	90%	0.04	0.09	0.02	0.02	42%	5%	53%	0.13

Explanatory notes:

(1) The estimates for methane emissions for each material when disposed in landfills without LFG recovery are shown in column "d." These values are the product of columns "b" and "c."

(2) The net GHG emissions from landfills with LFG recovery that flare LFG (column "g") are simply the methane generation (column "b") times the percentage of methane not recovered (15 percent, shown in column "e") times the percentage of remaining methane not oxidized (90 percent, shown in column "f"). (We estimated that by the year 2000 LFG recovery systems will have, on average, an 85 percent recovery efficiency; thus 15 percent of methane will not be recovered.)

Explanatory notes for Exhibit 7-3 (continued):

(3) To estimate the net GHG emissions from landfills with LFG recovery that generate electricity, we estimated the methane emissions and subtracted the avoided utility CO_2 emissions when methane is used to generate electricity. The calculations (and values) for column "i" are identical to those for column "g." Columns "j" and "k" account for avoided utility CO_2 emissions; the value in column "j" comes from Exhibit 7-4. Column "l" equals column "i" minus column "k."

(4) The expected percentage of methane from each type of landfill in 2000 is shown in columns "m," "n," and "o." The value for landfills with LFG recovery are based on the values of 58 percent of methane being generated at landfills with LFG recovery, and 9 percent of these landfills flaring the LFG rather than generating electricity.

(5) Finally, to estimate the total net GHG emissions from landfilling of each type of material, we used the GHG emissions for each category of landfill and the percentage of methane generated at each type of landfill to develop a weighted average across all landfills. The results are shown in column "p."

Exhibit 7-4

**Calculation to Estimate Utility GHGs Avoided
Through Combustion of Landfill Methane**

Step	Value	Source
Metric tons CH_4/MTCE CH_4	0.15	1/((12/44)*24.5): Global warming potential of 24.5 for CH_4
Grams CH_4/metric ton CH_4	1.00E+06	Physical constant
Cubic ft. CH_4/gram CH_4	0.05	1/20: 20 grams per cubic foot of methane at standard temperature and pressure
BTUs/cubic ft. CH_4	1,000	"Opportunity for LF Gas Energy Recovery in FL [Working Draft]," USEPA/OAR May 95, p. 2-11
kWh electricity generated/BTU	0.00008	1/13,000: from "Opportunity" report p. 2-11, assumes use of internal combustion engines
kWh electricity delivered/kWh electricity generated	0.91	U.S. DOE, EIA, "Annual Energy Review 1993 (Washington, DC: DOE/EIA) July 1994, p. 252
BTUs/kWh electricity delivered	3,412	Physical constant
Kg. utility C avoided/BTU delivered electricity	5.112E-05	51.12 kg C/mmBTU del'd electricity, from carbon coefficients table
Metric Tons avoided utility C/kg utility C	0.001	1000 kg per metric ton
Ratio of MTCE avoided utility C per MTCE CH_4	0.09	Product from multiplying all factors

landfills that flare LFG.[108] By basing our analysis on projected LFG recovery by the year 2000 (and the projected LFG recovery efficiency in 2000), we avoided double-counting of GHG reductions between programs that reduce landfilling and programs that increase recovery of landfill methane.

Our results are shown in the final column of Exhibit 7-3. The materials with the highest rates of *net* GHG emissions from methane generation · office paper, corrugated boxes, food scraps, and newspaper · also have the highest *gross* methane generation, as shown in column "b" of Exhibit 7-3. The recovery of methane at landfills reduces the methane emissions for each material in proportionate amounts, but does not change the ranking of materials by methane emissions. Yard trimmings and mixed MSW have the lowest rates of net GHG emissions from methane generation.

The three sections of the exhibit providing GHG emissions estimates for each category of landfill (in columns "d," "g," and "l") may be used by local MSW planners to estimate GHG emissions from MSW from a given community. For this purpose, one should add to the values in the appropriate column the estimated transportation GHG emissions (the national average used in this study is 0.01 MTCE per ton), and subtract estimated carbon sequestration (as shown for each material in Exhibit 7-2).

In a separate analysis, EPA has estimated that in 2000, when most landfill methane will be captured, landfills will emit 24.5 million MTCE of methane,[109] as compared to 68.2 million MTCE in 1994.[110]

Anthropogenic Carbon Dioxide Emissions from Transportation of Wastes to a Landfill

We next estimated the anthropogenic carbon dioxide emissions from transporting waste materials to a landfill. We began with estimates provided by Franklin Associates, Ltd. for the amount of diesel fuel required per ton of waste material for (1) collecting and transporting the material to a landfill (297,000 BTUs), and (2) operating the landfill equipment (231,000 BTUs).[111] We converted these estimates to units of metric tons of carbon equivalent (MTCE) per short ton of yard trimmings, based on a carbon coefficient of 0.0208 MTCE per million BTUs of diesel fuel. This resulted in an estimate of 0.01 MTCE of anthropogenic CO_2 emissions per short ton of material landfilled.

7.3   NET GHG EMISSIONS FROM LANDFILLING

To determine the net GHG emissions from landfilling each material (in absolute terms), we began with the net GHG emissions from methane generation, subtracted carbon sequestration, and added transportation CO_2 emissions. The results are shown in Exhibit 7-5.

Only one material, office paper, has net GHG emissions when landfilled of at least 0.1 MTCE per ton (because its methane emissions far exceed its landfill carbon sequestration). Food scraps, corrugated

---

[108] Memorandum from Cindy Jacobs, op cit.

[109] *Ibid.*

[110] U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1994*, EPA 230-R-96-006 (November 1995) p. 80.

[111] Franklin Associates, Ltd., *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (Stamford, CT: Keep America Beautiful), p. I-5.

Exhibit 7-5
Net GHG Emissions from Landfilling

(a) Material	(b) Net GHG Emissions from CH$_4$ Generation (MTCE/Wet Ton)	(c) Net Carbon Sequestration (MTCE/Wet Ton)	(d) GHG Emissions from Transportation (MTCE/Wet Ton)	(e) Net GHG Emissions from Landfilling (MTCE/Wet Ton)
Newspaper	0.13	0.34	0.01	-0.21
Office Paper	0.58	0.04	0.01	0.56
Corrugated Cardboard	0.26	0.23	0.01	0.04
Aluminum Cans	0.00	0.00	0.01	0.01
Steel Cans	0.00	0.00	0.01	0.01
HDPE	0.00	0.00	0.01	0.01
LDPE	0.00	0.00	0.01	0.01
PET	0.00	0.00	0.01	0.01
Food Scraps	0.16	0.08	0.01	0.09
Grass	0.10	0.08	0.01	0.04
Leaves	0.08	0.30	0.01	-0.21
Branches	0.08	0.21	0.01	-0.12
Yard Trimmings	0.09	0.17	0.01	-0.07
Mixed MSW	0.13	0.14	0.01	0.00

Explanatory notes: The net GHG emissions from methane generation, shown in column "b" of the exhibit, were simply copied from column "p" of Exhibit 7-3. The carbon sequestration values in column "c" of this exhibit were copied from column "e" of Exhibit 7-2. The GHG emissions from transportation in column "d" of this exhibit were developed as described in the text. The net GHG emissions for each material were determined by summing the values in columns "b" and "d," and then subtracting the value in column "c." The results are shown in column "e."

boxes, and grass have lower net GHG emissions; the metals and plastics have small transportation-related emissions (0.01 MTCE per ton). All the other materials appear to have carbon sequestration that exceeds their methane emissions, and so result in negative net GHG emissions when landfilled.[112]

7.4   LIMITATIONS

Perhaps the most important caveat is that the analysis is based on a single set of laboratory experiments conducted by Dr. Morton Barlaz. While researchers other than Barlaz have conducted laboratory studies that track the degradation of mixed MSW, Barlaz's experiments were the only ones we identified that rigorously tested different materials individually. Barlaz is recognized as an expert on the degradation of different fractions of MSW under anaerobic conditions, and his findings with respect to the methane potential of mixed MSW are within the range used by landfill gas developers. Nevertheless, given the sensitivity of the landfill results to estimated methane generation and carbon sequestration, we recognize that more research is needed in this area.

Another important caveat is that we estimated that 58 percent of MSW landfill methane generated in the year 2000 would be generated at landfills with LFG recovery systems. This would be an increase from the estimated 17 percent of landfill methane generated at landfills with LFG recovery in 1995. The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate. Because of the high global warming potential for methane, small changes in the LFG recovery rate by the year 2000 could have a large effect on the net GHG impacts of landfilling each material, and on the ranking of landfilling relative to other MSW management options. The effects of different rates of LFG recovery by the year 2000 are shown in Exhibit 7-6. Column "b" of the exhibit shows net GHG emissions at the 1995 recovery rate of 17 percent. The remaining columns show net GHG emissions at increasing LFG recovery rates, up to a 60 percent recovery rate (rounded up from 58 percent, the rate projected for 2000). As the exhibit shows, the net GHG emissions for landfilling mixed MSW are positive at lower rates of recovery, and turn negative only when the LFG recovery rate exceeds 50 percent. At the local level, the GHG emissions from landfilling MSW are quite different depending on whether the local landfill has LFG recovery, as shown in Exhibit 7-3.

On the national level, this analysis was based on LFG recovery levels expected by the year 2000. Because some landfill methane emissions prior to 2000 will not be recovered at the year 2000 levels, keeping organic materials out of landfills prior to the year 2000 will have GHG benefits in excess of those estimated here. A related point is that the analysis does not account for the timing of methane generation, which can occur for years after waste is landfilled. The values listed in this chapter represent total methane generated, over time, per ton of waste landfilled. To the extent that LFG recovery rates shift dramatically over time, these shifts are not reflected in the analysis. In addition, landfills with LFG recovery will be permitted, under EPA regulations, to remove the LFG recovery equipment when three conditions are met: (1) the landfill is permanently closed, (2) LFG has been collected continuously for at least 15 years, and (3) the landfill emits less than 50 metric tons of nonmethane organic compounds per year.[113] Although the removal of LFG recovery equipment will permit methane from closed landfills to escape into the

---

[112] Note that the components of yard trimmings - grass, leaves, and branches - have substantially different net GHG emissions when landfilled. Grass has small positive net GHG emissions, while leaves and branches have substantial negative GHG emissions (due to landfill carbon sequestration).

[113] Federal Register, Vol. 61, No. 49, p. 9907.

Exhibit 7-6
Net GHG Emissions from Landfilling

Sensitivity Analysis: Varying the Percentage of Waste Disposed
at Landfills with Methane Recovery

(a) Material	(b) 17% of waste disposed at landfills with LFG recovery	(c) 30% of waste disposed at landfills with LFG recovery	(d) 40% of waste disposed at landfills with LFG recovery	(e) 50% of waste disposed at landfills with LFG recovery	(f) 60% of waste disposed at landfills with LFG recovery
Newspaper	-0.10	-0.14	-0.16	-0.19	-0.21
Office Paper	1.04	0.89	0.77	0.65	0.54
Corrugated Cardboard	0.26	0.19	0.14	0.08	0.03
Food Scraps	0.22	0.18	0.15	0.11	0.08
Grass	0.12	0.09	0.07	0.05	0.03
Leaves	-0.15	-0.17	-0.19	-0.20	-0.22
Branches	-0.05	-0.07	-0.09	-0.10	-0.12
Yard Trimmings	0.01	-0.01	-0.03	-0.05	-0.07
Mixed MSW	0.11	0.07	0.05	0.02	-0.01

Note: Of the methane that is captured, we assumed that 9% is flared and 91% is recovered for energy.

Explanatory note: In every case we assumed that for methane that is captured, the proportions flared versus combusted for energy recovery are the same as shown in columns "n" and "o" of Exhibit 7-3.

atmosphere, the amounts of methane emitted should be relatively small, because of the relatively long time period required for LFG collection before LFG recovery equipment is removed.

It is also likely that ongoing shifts in the use of landfill cover and liner systems could influence the rate of methane generation and collection. As more landfills install effective covers and implement controls to keep water and other liquids out, conditions will be less favorable for degradation of organic wastes. Over the long term, it is possible that this will result in a decrease in methane generation and an increase in carbon sequestration. Moreover, Dr. Barlaz believes that the methane yields from his laboratory experiments are likely to be higher than methane yields in a landfill, because the laboratory experiments were designed to generate the maximum amount of methane possible. If the methane yields used in this analysis are higher than yields in a landfill, the net GHG emissions from landfilling organic materials would be lower than estimated here.

We assumed that once wastes are disposed in a landfill, they are never removed. In other words, we assumed that landfills are never "mined." (A number of communities have mined their landfills · removing and combusting the waste · in order to create more space for continued disposal of waste in the landfill.) To the extent that landfills are mined in the future, it is incorrect to assume that carbon sequestered in a landfill will remain sequestered. For example, if landfilled wastes are later combusted, the carbon that was sequestered in the landfill will be oxidized to CO_2 in the combustor.

For landfilling of yard trimmings (and other organic materials), we assumed that all carbon storage in a landfill environment is incremental to the storage that occurs in a non-landfill environment. In other words, we assumed that in a baseline where yard trimmings are returned to the soil, all of the carbon is decomposed relatively rapidly (i.e., within several years) to CO_2, and there is no long-term carbon storage. This approach differs somewhat from the one used in the chapter on composting, where we estimated the incremental carbon storage without regard to the absolute value of carbon storage in the baseline. To the extent that long-term carbon storage occurs in the baseline, the estimates of net GHG emissions reported here are understated.

Finally, our spreadsheet analysis is limited by the assumptions that were made at various steps in the analysis, as described throughout this chapter. The key assumptions that have not already been discussed as limitations are the assumptions used in developing "corrected" methane yields for organic materials in MSW. Because of the high global warming potential of methane, a small difference between estimated and actual methane generation values would have a large effect on the GHG impacts of landfilling, and on the ranking of landfilling relative to other MSW management options.